Spatial solitons in an optically pumped semiconductor microresonator

V. B. Taranenko, C. O. Weiss
Physikalisch-Technische Bundesanstalt 38116 Braunschweig, Germany

We show experimentally and numerically the existence of stable spatial solitons in an optically pumped semiconductor microresonator. We demonstrate that the pump substantially reduces the light intensity necessary to sustain the solitons and thereby reduces destabilizing thermal effects. We demonstrate coherent switching on and off of bright solitons. We discuss differences between pumped and unpumped below-bandgap-solitons.

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Spatial solitons in semiconductor microresonators [1,2] are self-trapped light beams which can form due to both transverse (e.g., self-focusing) and longitudinal (nonlinear resonance [3]) nonlinear effects. These nonlinear effects can act in the same sense or oppositely, with the consequence of reduced soliton stability in the later case. Thus choice of nonlinear resonator parameters suited best for sustaining stable solitons is important. The best-suited schemes are unpumped microresonator excited above bandgap [4] and optically pumped microresonator excited below bandgap [5].

Here we pump a semiconductor microresonator optically in a range up to the lasing threshold and study formation of switched structures. We show experimentally and numerically the existence of the resonator solitons in the pumped microresonators. We demonstrate that the pumping substantially reduces the light intensity necessary to sustain and switch the solitons (diminishing thermal problems as a side effect) so that semiconductor laser diodes are sufficient for sustaining solitons. We discuss differences between pumped and unpumped solitons below bandgap.

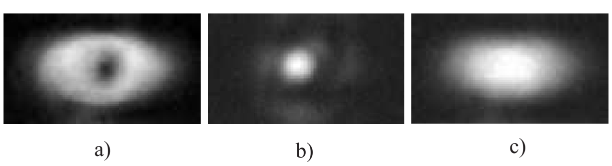

FIG. 1. Intensity snapshots of typical structures observed in reflection from pumped (below transparency) semiconductor microresonator illuminated near resonance showing bright (a) and dark (b) soliton.
The illuminating beam from the laser diode has an elliptical shape (c).

We pump a bistable quantum-well (GaAs/GaAlAs) microresonator using either a tunable Ti:sapphire laser or a high power multimode laser diode. The pumped area of the resonator is illuminated additionally by a focused beam from a single-mode laser diode that provides quite large Fresnel number ($\sim$100) and near resonant illumination of the resonator. The main control parameters in the experiment are the resonator detuning and intensities of the illumination and pump.

Observations are done in reflection since the substrate of the microresonator structure is opaque at the working wavelengths: dark switched structures in reflection correspond to bright ones in transmission and vice versa. Switched structures formed in the illuminated beam cross section were monitored in the plane of the microresonator in two ways: (i) A CCD camera with electro-optical shutter recorded 2D snapshots of switched structures. (ii) A fast and small aperture photo detector monitored local dynamics.

Switched structures observed (Fig. 1 a,b) manifest themselves as resonator solitons: 1) they are of the size ($\sim$10 μm) expected for such solitons [1]; 2) they are round spots whose size and shape are independent on the intensity and shape of the illuminating beam (e.g., elliptical beam shape as shown in Fig. 1c); 3) they are robust against perturbations of the illuminating light intensity; 4) they are bistable, i.e. they can be switched on (Fig. 2a) and off (Fig. 2b) by sharply focused address pulses.

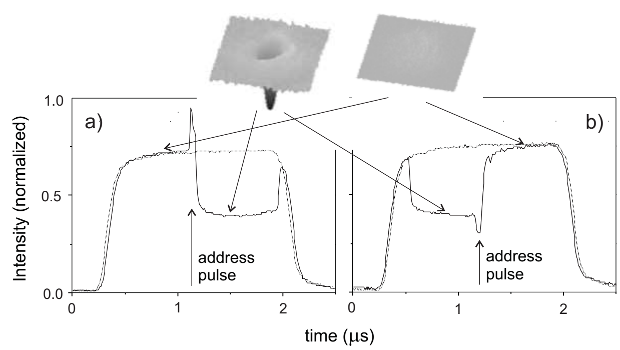

FIG. 2. Recording of switching-on (a) and switching-off (b) of a bright soliton. Vertical arrows mark the application of address pulses. Dotted traces: incident intensity. The insets show soliton and unswitched state in 3D representation.

This soliton nature of the observed switched structures is supported by numerical simulations of the intracavity

field structures (in 2D) using the model equations for the pumped semiconductor microresonator driven by a plane wave [5]. Fig. 3 shows typical examples of calculated resonator solitons below bandgap. Bright solitons have a large existence range in the pumped case (Fig. 3b), dark solitons exist, though with smaller range of stability, in the unpumped case (Fig. 3a). Parameter domains of existence of resonator solitons are related to those of optical bistability for plane waves, are shown in Fig. 3.

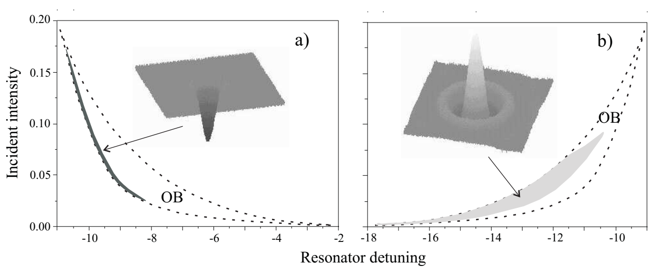

FIG. 3. Results of numerical simulations of below bandgap (purely dispersive) solitons using the model equations for unpumped (a) and pumped above "transparency" point (b) microresonator. Insets are dark (a) and bright (b) solitons. Shaded areas are domains of existence of resonator solitons. Areas limited by dashed lines are optical bistability domains for plane waves.

Analysis shows that increase of the pump intensity leads to shrinking of the resonator solitons' existence domain and shifting towards low intensity of the light sustaining the solitons (Such reduction of the sustaining light intensity was observed experimentally in [5]).

When the pump intensity approaches the transparency point of the semiconductor material, the resonator solitons' domain of existence disappears. It reappears above the transparency point. In the experiment we have quite strong contribution of the imaginary part (absorption/gain) of the complex nonlinearity at the working wavelength (854 nm). Therefore the transparency point is very close to the lasing threshold so that inversion without lasing is difficult to realize.

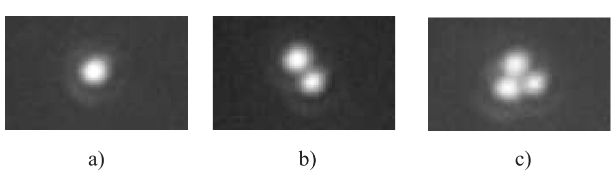

FIG. 4. Intensity snapshots of typical beam structures at optical pump intensities slightly above lasing threshold (pump increases from (a) to (c)).

Slightly above threshold we observe in presence of illumination structures (Fig. 4) reminiscent of the solitons in electrically pumped resonators [6].

In summary, optically pumped semiconductor resonators are well suited for sustaining solitons below bandgap:(i) background light intensity necessary to sustain and switch resonator solitons is substantially reduced by the pumping and therefore destabilizing thermal effects are minimized, (ii) above the transparency point only the dispersive part of semiconductor nonlinearity stabilizes a soliton, therefore the domain of existence of "below bandgap" (purely dispersive) bright solitons can be quite large. Moreover optical as opposed to electrical pumping allows more homogeneous pumping conditions [7]. This suggests that optically pumped resonators lend themselves more readily for localization and motion control of solitons then electrically pumped ones.

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